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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF SHORT TWO-DIMENSIONAL SUBSONIC DIFFUSERS

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SUMMARY

Several short two-dimensional subsonic diffusers were tested over a range of throat Mach numbers from 0.3 to 0.9. The designs incorporated an effective diffusion angle of approximately 30° and an area ratio of 3. Included were: (1) a 30° faired diffuser with four variations of screens and vanes, (2) a diffuser in which the longitudinal velocity distribution is a step function and which utilizes suction early in the diffusion process, and (3) a vortex-trap design using flow injection near the throat and suction at the diffuser exit. For comparison, a 10° faired diffuser was also tested.

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At a throat Mach number of 0.7, the resulting profile distortion of the unmodified 30° diffuser was diminished from about 11 to approximately 4 percent by using any of the configurations. The pressure recoveries of the 30° diffusers were 0.935, 0.935, and 0.865, respectively, for the unmodified design, the vane diffuser, and the screen installation; pressure recovery was 0.930 for both the vortex-trap and step-velocity diffusers. The 10° diffuser yielded a pressure recovery of 0.96.

INTRODUCTION

Recently, there has been much interest in short efficient subsonic diffusers because of their potentially simple installation and reduced weights. As a continuation of the general diffusion problems being investigated at the NACA Lewis laboratory, diffusers with high rates of expansion were tested to determine the associated performance penalties. Previous work conducted on axial symmetric (refs. 1 and 2) and two-dimensional subsonic diffusers (ref. 3) has indicated the feasibility of step-velocity and vortex-trap diffusers. (The step-velocity diffuser is one in which the longitudinal velocity distribution is a step function, and suction near the start of the diffusion process is utilized. The vortex-trap diffuser utilizes flow injection at the start of the diffusion process in addition to suction at the diffuser exit.) Axially symmetric subsonic diffusers utilizing suction and injection were also tested at the NACA Langley laboratory.

The present experimental study was conducted to investigate the pressure recovery and profiles associated with several types of subsonic diffuser of extreme design (30° effective two-dimensional diffusion angle with area ratio of 3). Because of the preliminary nature of the investigation, no attempt was made to simulate shocks or upstream boundary-layer separations that might occur in the diffuser passage of inlets to turbojet or ram-jet engines. Therefore, the results of the present tests are not directly applicable to the case of inlet diffusers. The investigation extends existing information to higher throat Mach numbers, a larger effective diffusion angle (30°), and a larger diffusion area ratio. 3927

SYMBOLS

The following symbols are used in this report:

M_t throat Mach number

P_{av} average (area weighted) total pressure at rake station

P_0 total pressure ahead of bellmouth

ΔP maximum total pressure minus the minimum total pressure from profile at rake station (neglecting pressures less than 0.25 in. from the walls)

p static pressure

x,y longitudinal and duct height coordinates, in.

APPARATUS AND PROCEDURE

The tests were conducted in one of the Lewis laboratory's atmospheric intake duct stations using dry air. The air flow was controlled by a butterfly valve located about 3 to 4 duct heights downstream of the measuring station of the short diffusers (fig. 1). Ahead of the diffuser, the flow was accelerated by means of a convergent two-dimensional channel indicated in the photograph of figure 1 and in the schematic sketch of figure 2. Although the convergent channel is unsymmetrical, the total-pressure profiles across the throat are uniform to within 1/16 inch of the walls (limit of the probe effectiveness).

Six subsonic diffusers were tested (fig. 2), all of which had a throat cross-sectional dimension of 1 by 4 inches and a rake station cross-sectional dimension of 3 by 4 inches. Thus a diffusion area ratio of 3 existed for all the models. Two of the designs did not incorporate any vanes, screens, suction or injection devices, and were tested principally as a comparison standard for the more complex models. One of these reference diffusers had an effective expansion angle equal to that of a 10° two-dimensional diffuser with straight walls, and is referred to as the 10° faired diffuser. The surface angles did not exceed 12° at any station (fig. 2(a)). The 10° expansion angle used as the main design criterion of this diffuser has been indicated (ref. 4) as the optimum for two-dimensional diffusers. A second reference diffuser (fig. 2(b)) was tested which used a 30° expansion angle. (Since the equivalent rate of area expansion of the more complex diffusers was about 30°, they could be considered as modifications of the 30° faired diffuser.)

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The 30° faired diffuser was modified with the addition of two partitions to form the vane diffuser (fig. 2(c)). These vanes were essentially straight with the exception of a curved final portion intended to straighten the flow at the diffuser exit. These two vanes split the passage into three sections each of which had an equivalent area expansion of 10°. Thus, by decreasing the rate of diffusion it was hoped that distortion would be improved, in spite of the increased friction surface, at only a small sacrifice in recovery. Another modification of the 30° faired diffuser, accomplished by the addition of canted (15° from normal) screens located at various positions along the diffuser, was also investigated (fig. 2(d)). Since the flow direction downstream of a canted screen lies between the normal of the screen and the impinging flow direction, it was thought that screens would help turn the flow toward the contoured wall and thereby alleviate boundary-layer separation in the diffuser (ref. 5). The screens tested were 0.011-inch wire, 14 by 18 mesh.

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The vortex-trap diffuser, the contour surface of which was entirely arbitrary, had an equivalent two-dimensional angular expansion of approximately 40° (fig. 2(e)). Downstream flow injection was incorporated near the beginning of the diffusion process, while suction was applied at the end of the process. This injected air was directed towards the suction slot. It was the purpose of these air controls to confine the existing vortex in a specified region of the diffuser and thus prevent it from sporadically shedding to form an unsteady flow pattern (side wall static-pressure measurements indicated that with injection a free vortex is present). This would, in turn, help the flow to negotiate the rapid turn in the diffuser.

The sixth and last diffuser, the step-velocity diffuser (fig. 2(f)), was contoured with a concave wall surface (having less curvature than the vortex-trap diffuser) and incorporated wall suction shortly beyond the beginning of the area expansion. The principle of the step-velocity diffuser is that the velocity is theoretically constant or monotonically increasing along the contoured wall except at a local point, where the velocity theoretically undergoes a step decrease. Thus boundary-layer separation should tend to occur only at a fixed point where it may be controlled by means of suction. Since no theory is available for the design of step-velocity diffusers for compressible flow, the incompressible flow solution (ref. 6) was used as a guide in the design.

Static pressures were obtained along the straight wall side of all the diffusers and along the contoured wall of the step-velocity diffuser. In addition, a rake was installed to obtain exit total-pressure profiles. The entrance flow in the throat was checked with a Pitot pressure probe and found to be uniform. The lateral profile of the flow from one straight side plate to another was checked for the 30° faired subsonic diffuser at a throat Mach number of 0.7. The profile of the flow was similar to a fully developed pipe flow with a distortion factor $\Delta P/P_{av}$ of 5 percent. A total-pressure tube was also installed upstream of the bellmouth in order to ascertain the pressure loss in the piping of dry air from the atmosphere to the model.

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The throat Mach number was varied in each of the diffusers by controlling the mass flow with a butterfly valve downstream of the diffuser (fig. 1). Four static-pressure orifices located at the throat section and a Pitot tube upstream of the bellmouth were used to calculate this Mach number. Suction slots were vented downstream of the butterfly control valve, while the air supply (atmospheric) for injection was regulated by a gate valve.

RESULTS AND DISCUSSION

Total-Pressure Recovery and Profile Distortion

The variation of diffuser total-pressure recovery and profile distortion as a function of throat Mach number for the various diffusers investigated is presented in figure 3. The 10° faired diffuser maintained a total-pressure distortion of 6 percent or less as the Mach number was raised to 0.93, however, the distortion of the 30° faired diffuser varied from 6 percent to approximately 22 percent as the throat Mach number was increased from 0.5 to 0.93 (fig. 3(a)). With the modification of vanes, vortex traps, or screens, the distortion was reduced to values less than 5 percent for Mach numbers below 0.7 (fig. 3(b)). Above this Mach number, the vane and vortex-trap diffuser profile deteriorated, while the distortion for the screen diffuser remained comparable with the 10° faired diffuser.

A comparison of the diffusers at a flow condition where the throat Mach number is roughly 0.7 (one-dimensional exit Mach number, 0.18) is made in the following table:

Subsonic diffuser	Total-pressure recovery	Profile distortion factor, percent
10° Faired	0.96	5.0
30° Faired	.935	11.5
Vane	.935	4.5
Screen	.865	3.2
Vortex-trap (90° Approx)	.930	3.0
Step-velocity (tested at M_t = 0.78 only)	.930	5.5

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The vane, vortex-trap, and step-velocity diffusers experienced about the same loss in pressure recovery as the unmodified 30° faired diffuser. All the subsonic diffusers with the exception of the 30° faired diffuser had comparable profile distortion factors. The use of vanes in the 30° faired diffuser decreased the percentage profile distortion factor from 11.5 to 4.5. Since the step-velocity diffuser was tested only at a throat Mach number of 0.78, its pressure recovery and distortion at a throat Mach number of 0.7 would probably be somewhat improved.

When the leading edge of the vanes extend upstream into the diffuser throat, the minimum area of the diffuser is reduced. Thus choking of the flow and hence severe penalties in pressure-recovery and profile distortion will occur at a lower measured Mach number. With the flow choked in the vane passages, the pressure-recovery and profile distortion curves of the vane diffuser shift toward higher distortions (fig. 3(b)).

In the use of screens, position is an important parameter. As the screens are moved upstream to the throat (position 3, fig. 2(d)), the pressure loss becomes very large (perhaps intolerable). Although the recovery was greatest for screen position 1, the distortion appeared to be smallest for an intermediate position. As an example (M_t = 0.70), the pressure recovery and profile distortion for screen position 1 were, respectively, 0.865 and 3.2 percent; for screen position 2, 0.835 and 1.5 percent; and for screen position 3 (M_t = 0.46), 0.76 and 15 percent.

The results in the table for the vortex-trap and step-velocity diffuser are for the particular combinations of suction and injection which proved best. When insufficient injection and suction were used (less than 8 percent of diffuser mass flow), the flow became erratic, changing back and forth from the performance indicated in the table to that obtained for the 30° faired diffuser.

An estimate was made of the pumping power required for the auxiliary air in the step-velocity or vortex-trap diffusers; it was assumed that the auxiliary air would be dumped at the diffuser inlet and that the pump would supply the required pressure rise. This pumping power would modify the performance of these diffusers by decreasing their effective pressure recovery by 0.015.

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Total-Pressure Profiles

Typical exit total-pressure profiles of the various diffusers are presented in figure 4 for a throat Mach number of approximately 0.7. It can be seen (fig. 4(a)) that each passage of the vane diffuser has a different level of total-pressure recovery, the highest being in the passage along the curved portion of the diffuser. This difference suggests that if a readjustment of the effective diffusion angle of each passage was made, distortion might be decreased still further.

For the diffuser with screens, figure 4(b) illustrates typical profiles at the diffuser exit for several screen positions. Because of the flow choking in screen position 3, the throat Mach number never exceeded 0.5. Typical profiles of the step-velocity and vortex-trap diffusers are presented in figure 4(c).

Longitudinal Static-Pressure Distributions

The static-pressure distribution along the step-velocity diffuser is compared with a theoretical value for incompressible flow in figure 5(a). The measured values were in poor agreement with the theory (ref. 6) possibly because of compressible-flow effects.

The static-pressure distribution along the remaining diffusers is presented in figure 5(b)(the static pressures at zero station do not correspond exactly with the throat Mach numbers, since these Mach numbers were calculated from an average of several pressures at the throat).

Visual Observation

The extremely distorted flow of the 30° faired diffuser is visible in figure 6(a). Note that the boundary layer flows straight back from the point of separation as soon as it detaches from the shoulder. This separation is delayed considerably by the use of vanes (fig. 6(b)). Because of the flow turning in the diffuser, there are centrifugal forces present in the main flow which cause boundary-layer cross flows. This is shown in figure 6(c) with liquid traces on the glass side walls. These cross flows may cause an undesirable boundary-layer accumulation in the corners and the walls of the subsonic diffuser.

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The effect of optimum screen positioning is observed in figure 7. Pressure data indicated that screen position 2 yielded the least distortion.

The effect of insufficient injection in the vortex-trap diffuser is depicted in figure 8. The dark stream in the center of the photographs is a carbon dioxide jet piped to the exit of the injection slot by means of a 3/8-inch tube and used to help visualize the low-density subsonic flow. The dark region that appears in the lower right portion of the schlieren is water-vapor condensation from the injected air.

In addition to the previously mentioned visual aids, tufts were used along the walls of the step-velocity diffuser. These tufts indicated severe cross-flow conditions on the concave wall section of the diffuser at certain flow conditions.

SUMMARY OF RESULTS

Several short shock-free subsonic diffusers were tested over a range of throat Mach number. These short diffusers used an effective diffusion angle of about 30° with an area ratio of 3. At a throat Mach number of 0.7, the result of profile distortion of the 30° diffuser was diminished from about 11 percent to approximately 4 percent by use of the configurations tested. The total-pressure recoveries of the 30° diffusers were 0.935, 0.935, and 0.865, respectively, for the unmodified design, the vane diffuser, and the screen installation; and 0.930 for both the vortex-trap and step-velocity diffusers. The 10° diffuser yielded a total-pressure recovery of 0.96.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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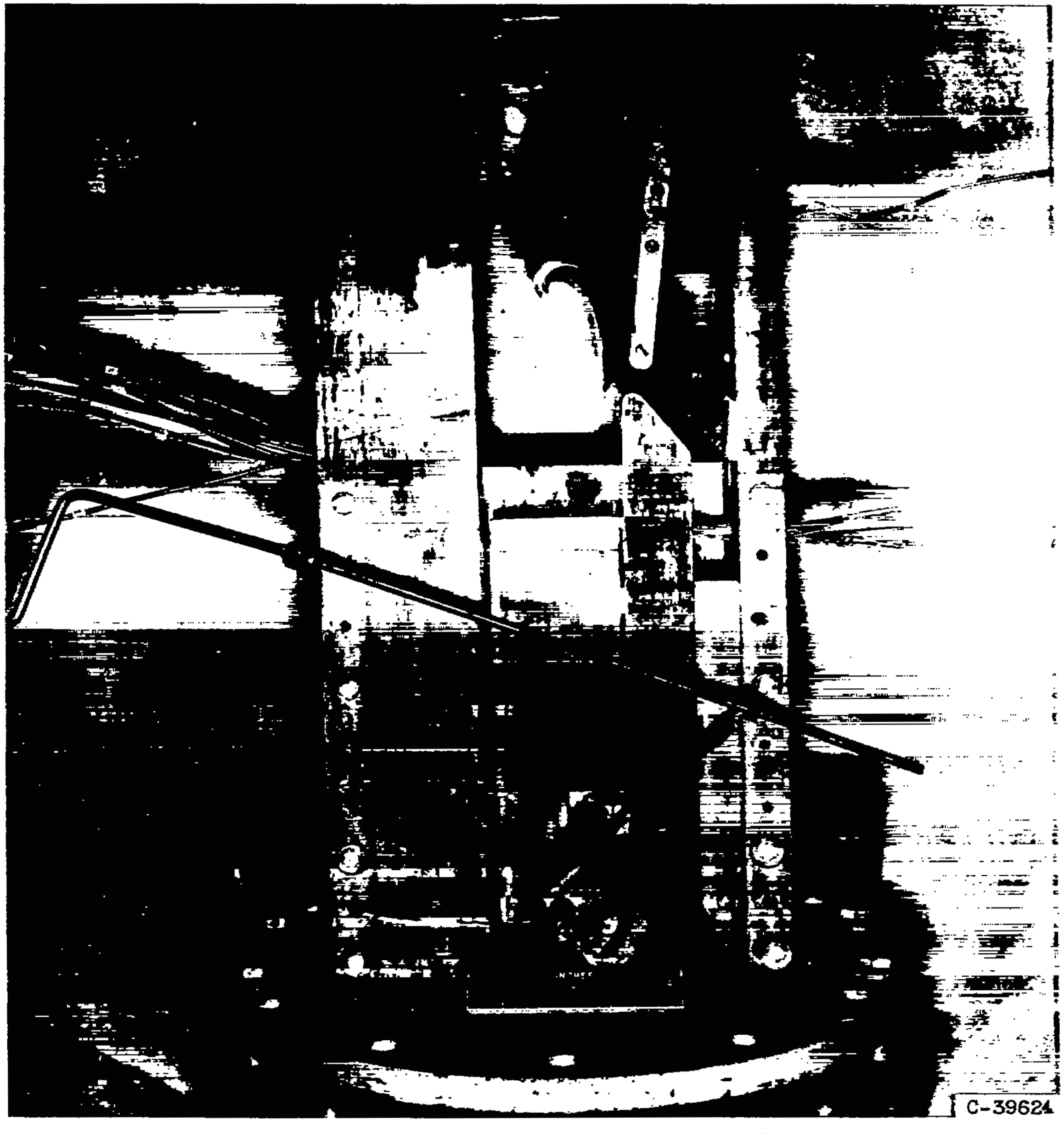

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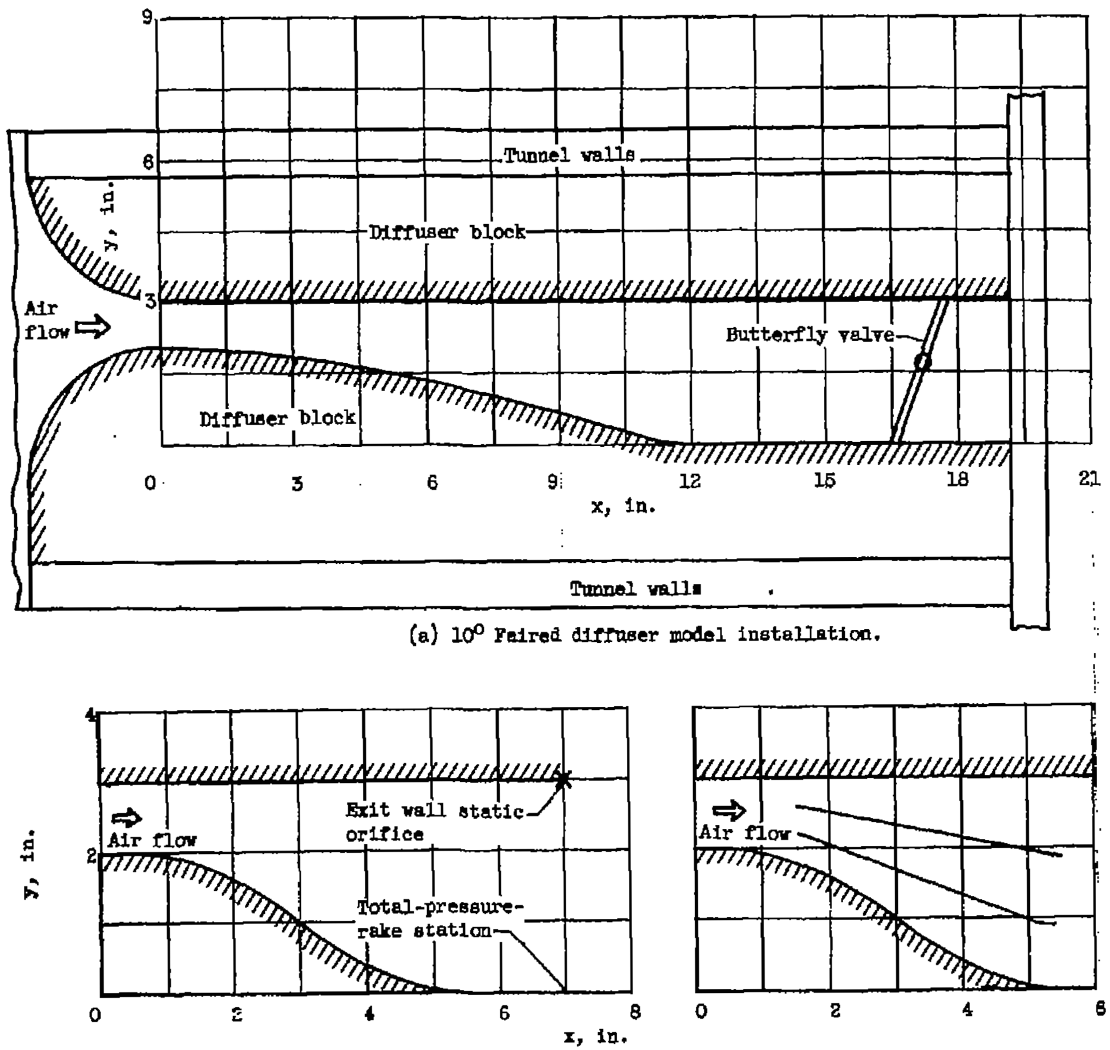
Figure 1. - Model installation of vortex-trap diffuser.



(a) 10° Faired diffuser model installation.

(b) 30° Faired diffuser.

(c) Vane diffuser.

Figure 2. - Subsonic diffusers.

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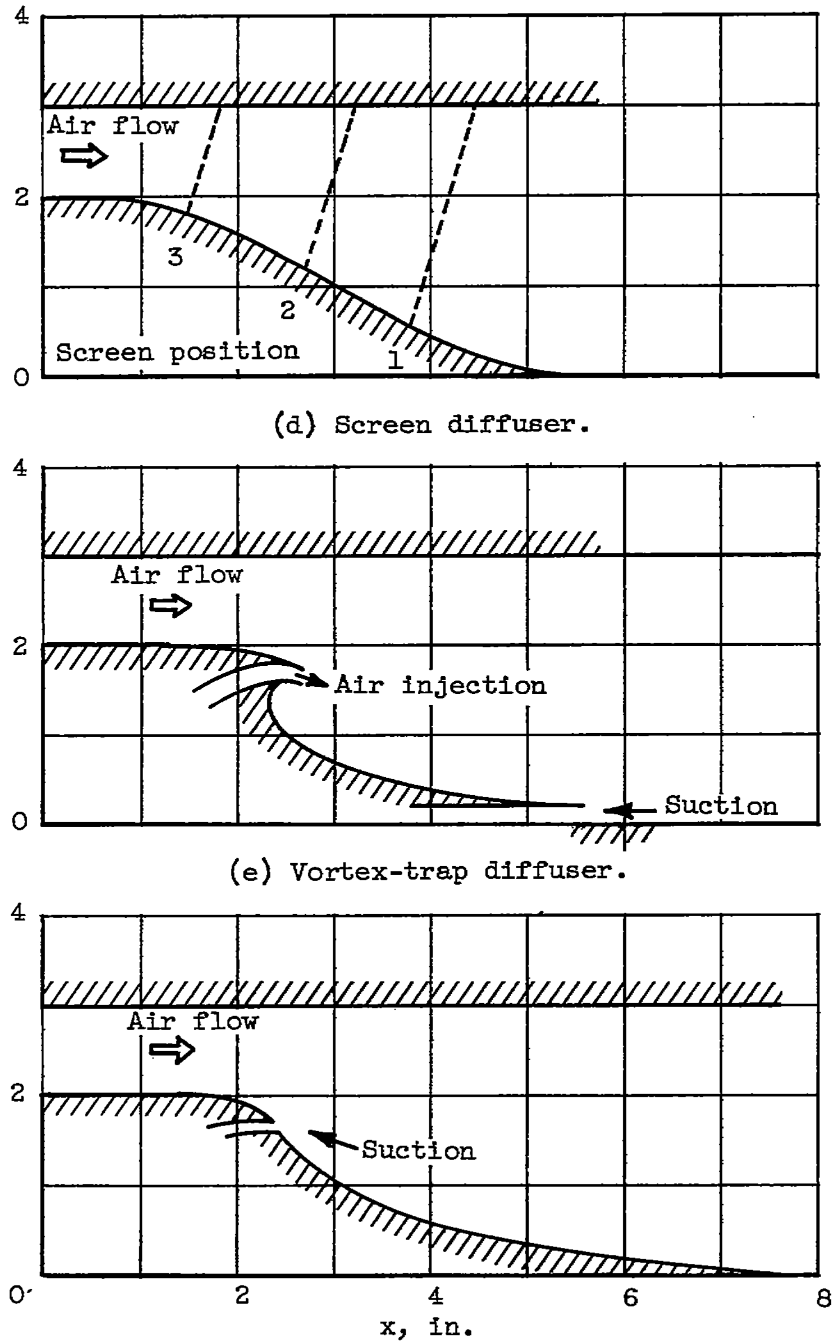
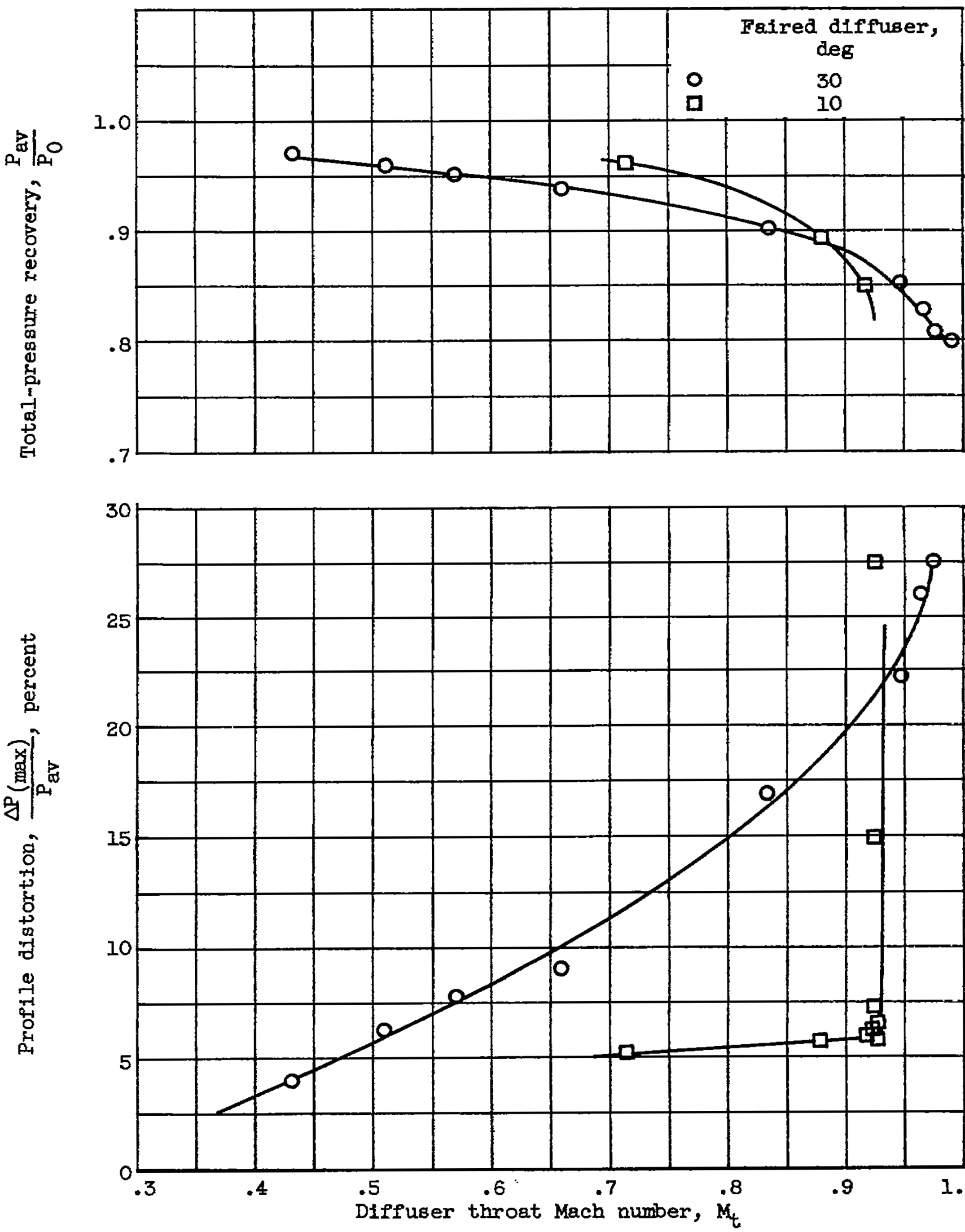


(d) Screen diffuser.

(e) Vortex-trap diffuser.

(f) Step-velocity diffuser.

Figure 2. - Concluded. Subsonic diffusers.



(a) 10° And 30° faired diffusers.

Figure 3. - Performance of subsonic diffusers at various diffuser throat Mach numbers.

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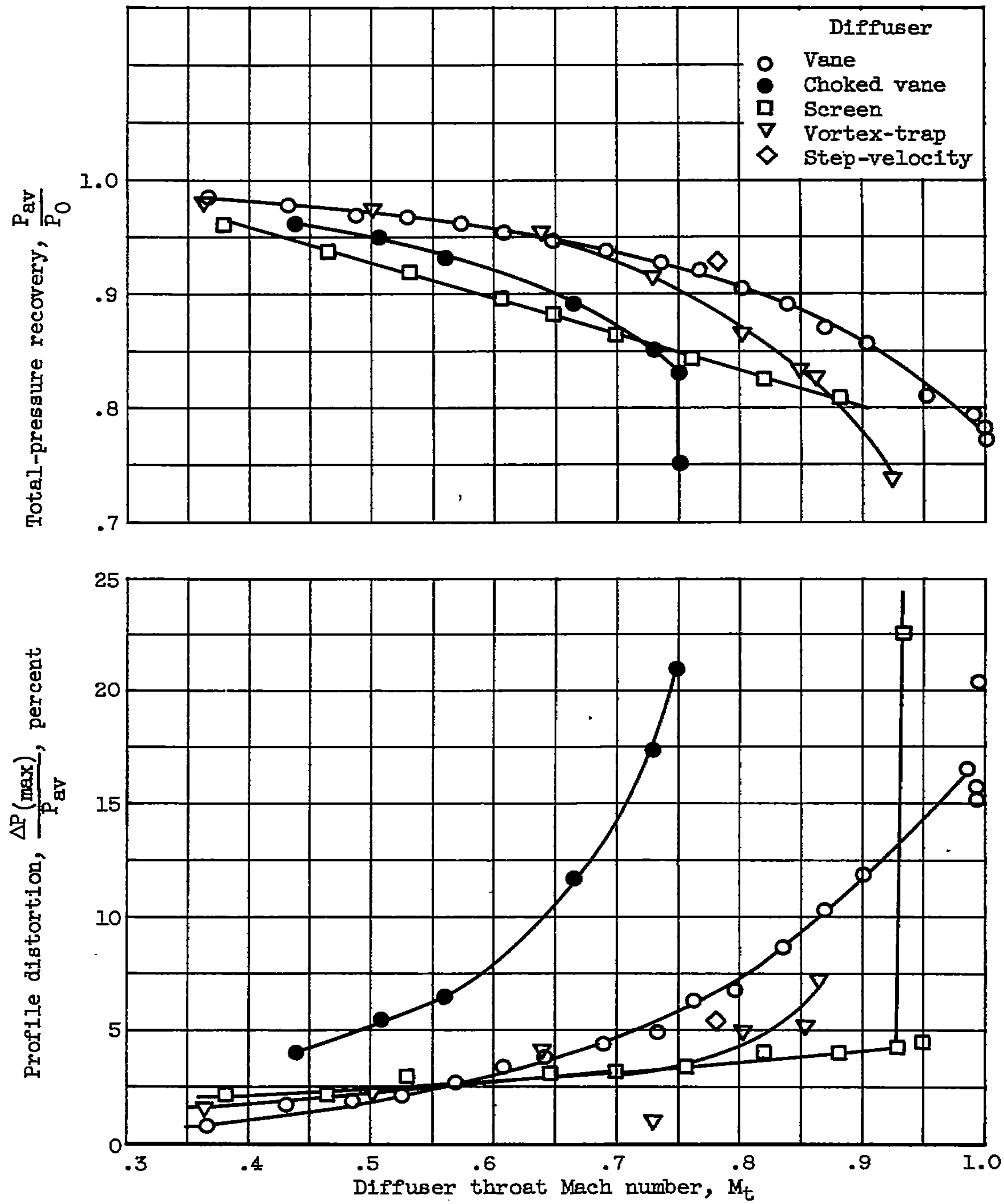
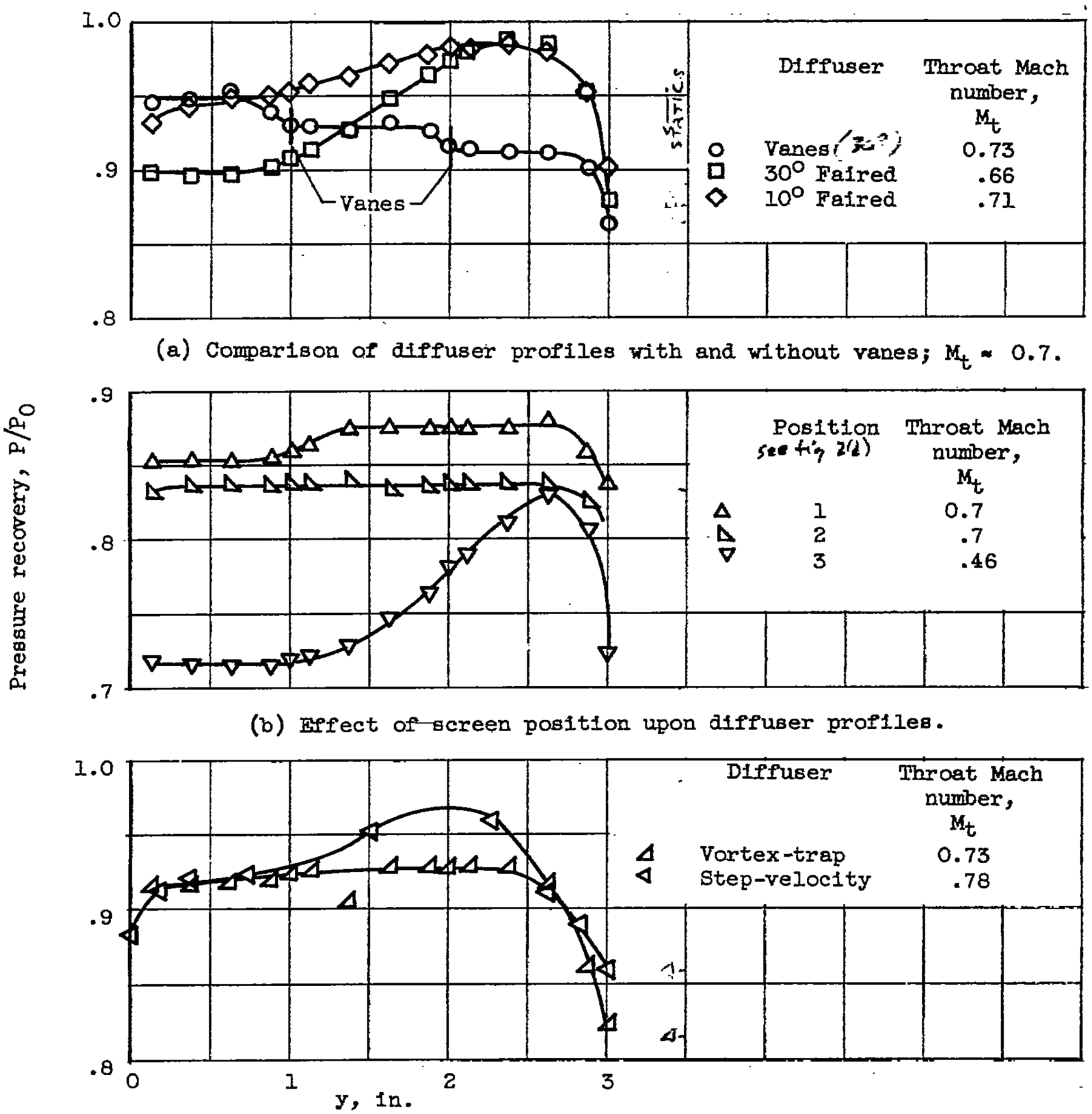


(b) Vane, screen, vortex-trap, and step-velocity diffusers.

Figure 3. - Concluded. Performance of subsonic diffusers at various diffuser throat Mach numbers.



(a) Comparison of diffuser profiles with and without vanes; $M_t \approx 0.7$.

(b) Effect of ~~screen~~ screen position upon diffuser profiles.

(c) Vortex-trap and step-velocity diffuser.

Figure 4. - Exit total-pressure profiles of various diffusers.

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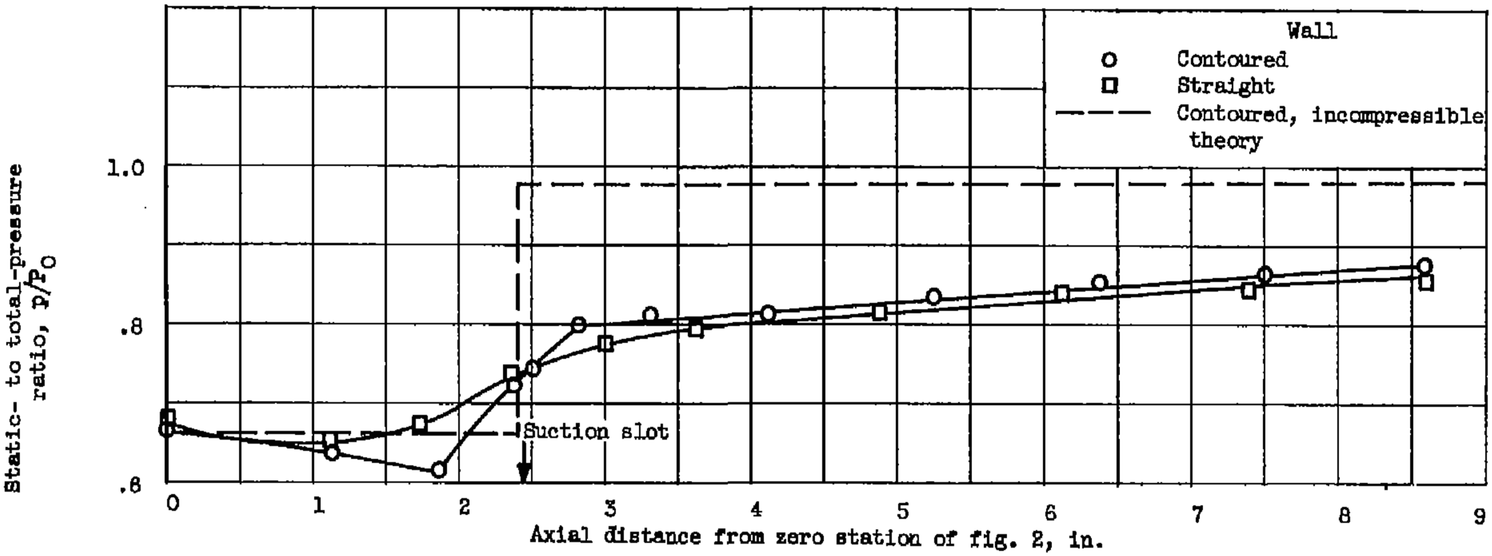
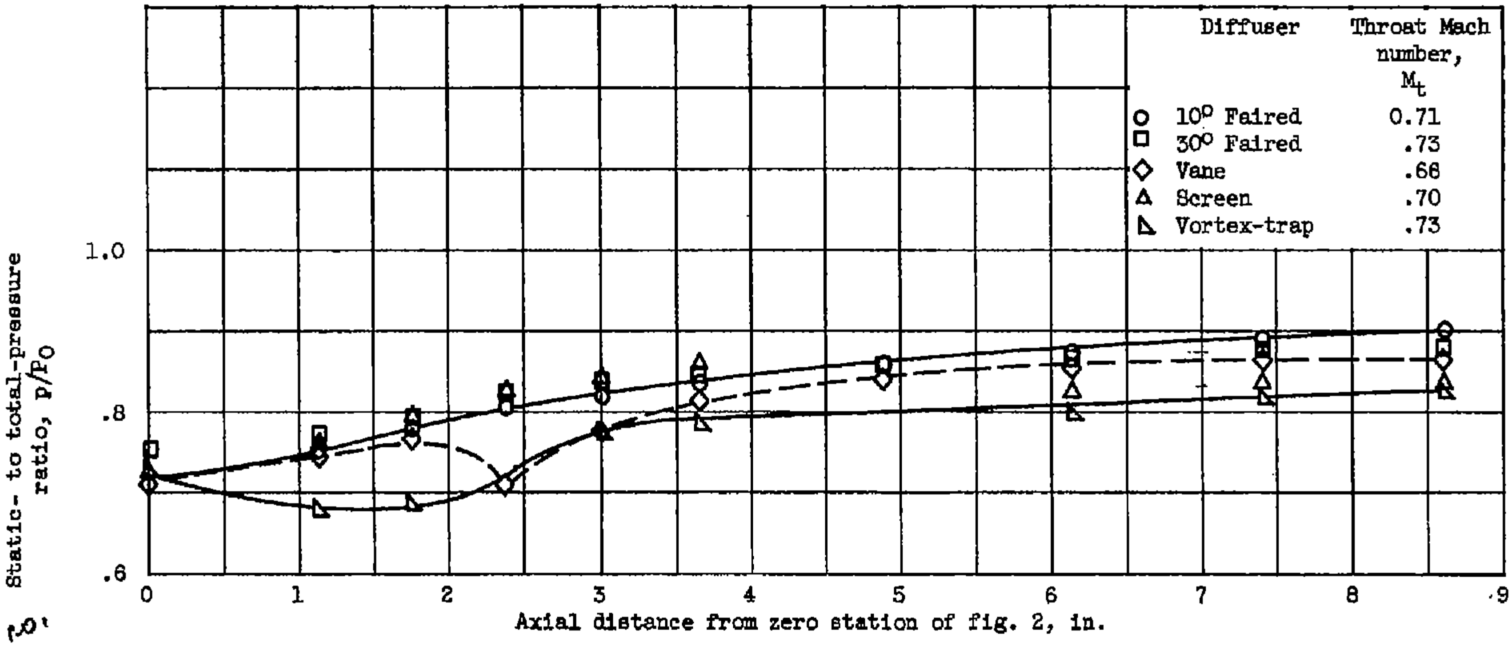


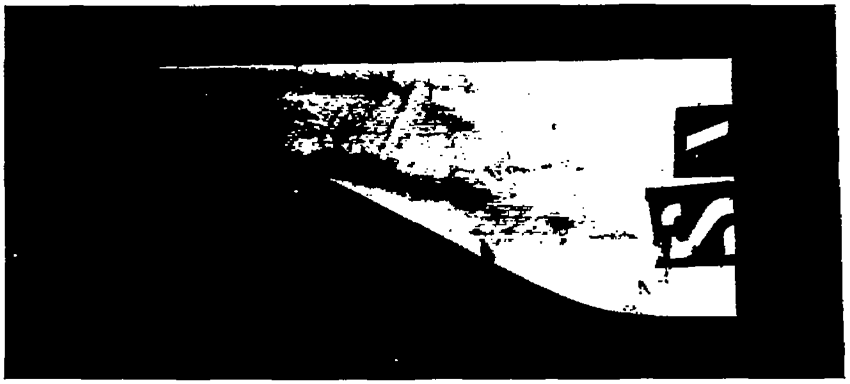
(a) Step-velocity diffuser; throat Mach number of 0.78.

Figure 5. - Wall static-pressure distributions through various diffusers.

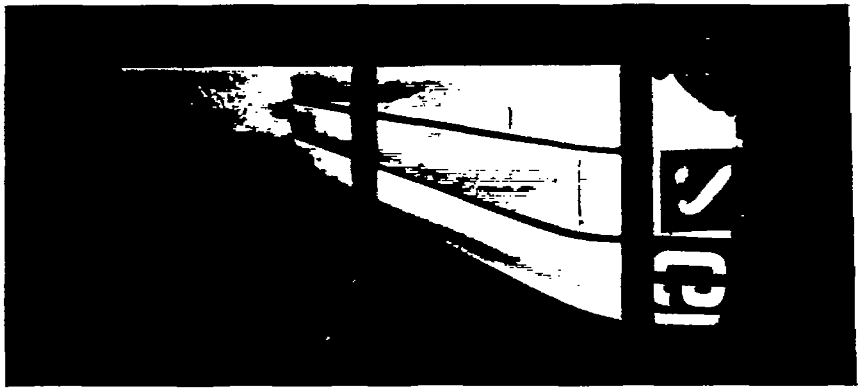


(b) Straight-wall pressures of 10° and 30° faired, screen, vane, and vortex-trap diffusers.

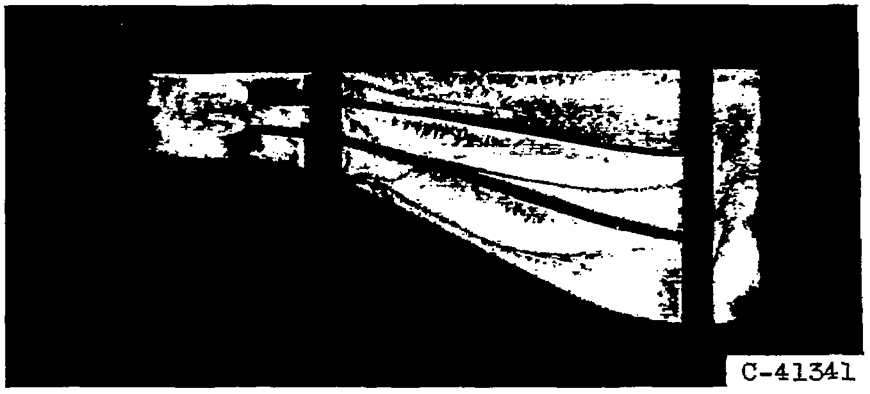
Figure 5. - Concluded. Wall static-pressure distributions through various diffusers.



(a) 30° Faired diffuser; schlieren photograph.

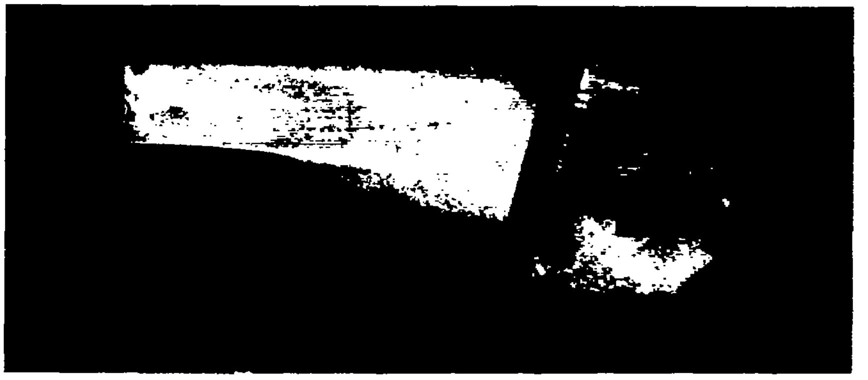


(b) Vane diffuser; schlieren photograph.



(c) Vane diffuser; liquid injection showing effect of boundary-layer cross flow.

Figure 6. - Flow with 30° faired diffuser and with vane diffuser, throat Mach number, 0.7.



(a) Screen position 1, throat Mach number, 0.7.

(b) Screen position 2, throat Mach number, 0.7.

(c) Screen position 3, throat Mach number, 0.46.

Figure 7. - Schlieren photographs of flow with screen diffuser.

(a) Optimum suction and injection (approximately 8 percent of diffuser mass flow).

(b) Insufficient injection (less than 8 percent of diffuser mass flow).

Figure 8. - Schlieren photographs of flow with vortex-trap diffuser; throat Mach number, 0.7.